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Torque Density Improvement of Spoke Type BLDC Motor Using Hollow Rotor Topology

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TORQUE DENSITY IMPROVEMENT OF SPOKE TYPE BLDC MOTOR USING HOLLOW ROTOR TOPOLOGY

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DECLARATION

I declare that this thesis entitled "Torque Density Improvement of Spoke Type BLDC Motor Using Hollow Rotor Topology" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Farina Binti Sulaiman

Date : 31/10/2016

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

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Date : 31/10/2016

DEDICATION

To my husband and cutest daughter,

Mohd Azam Bin Tumijan and Khaulah al Khansa Binti Mohd Azam

My beloved parents,

Sulaiman Bin Jamaldeen, Gafurah Binti Shadi Khan and Manirah Binti Saleh

Lastly, my brothers and sister,

Mohammed Feroz Bin Sulaiman, Mohammed Faizal Bin Sulaiman, Fazillah Binti Sulaiman, Mohammed Fared Bin Sulaiman

ABSTRACT

A spoke type motor has high torque because it uses reluctance torque and magnetic torque simultaneously. Rotor spoke type BLDC have a large amount of circling flux below the permanent magnet. This means that the motor cannot operates in optimum condition due to large unused flux. To overcome this problem, thickness of inner rotor radius, r_3 is increase in order to study effect of edge magnet. Hollow rotor is designed to maximize the usage of flux by contributing all the unused flux to circulate around coil. Finite Element Method (FEM) is used to analyze the characteristic and performance of spoke type BLDC machine which include radial flux density, tangential flux density, back emf, inductance, flux linkage and torque. Then, a new spoke type BLDC motor called as Hollow rotor is proposed to overcome the usage of flux in spoke type BLDC motor. For the methodology, some value for design of stator, coil and permanent magnet are selected based on the required specification. After that, electromagnetic characteristic of the selected conventional model is analyzed and parameter for the flux leakage reduction is carried out. In addition, performance analysis of the proposed hollow-rotor also been carried out. Hollow rotor spoke type BLDC motor is been fabricated and experimentally evaluated. The simulation results from the FEM are verified with the measurement result in term of back emf, static torque, torque vs speed, mechanical power, output power, dynamic torque and efficiency and has shown a good agreement. Torque density of hollow-rotor increase almost 50% compared to conventional spoke type BLDC motor. In conclusions, the research proposed a new improvement in spoke type BLDC motor that could provide higher torque density with reasonable motor size. Finally, this thesis provides guidelines, suggestions and proposes a better improved structure in designing BLDC motor.

ABSTRAK

Motor jenis spoke mempunyai tork yang tinggi kerana ia menggunakan tork keengganan dan tork magnet serentak. Rotor bercakap jenis BLDC mempunyai sejumlah besar mengelilingi fluks bawah magnet kekal. Ini bermakna bahawa motor tidak boleh beroperasi dalam keadaan optimum kerana fluks tidak digunakan besar. Untuk mengatasi masalah ini, ketebalan dalaman pemutar radius r_3 *adalah peningkatan dalam usaha untuk mengkaji kesan daya magnet. rotor Hollow adalah reka bentuk untuk memaksimumkan penggunaan fluks dengan menyumbang semua fluks yang tidak digunakan untuk mengedarkan sekitar gegelung. Kaedah Unsur Terhingga (FEM) digunakan untuk menganalisis ciri jenis spoke mesin BLDC termasuk ketumpatan fluks jejarian, ketumpatan fluks tangen, belakang emf, kearuhan, hubungan fluks dan tork. Kemudian, sejenis spoke BLDC motor baru yang dipanggil sebagai pemutar Hollow dicadangkan untuk mengatasi penggunaan fluks dalam jenis spoke BLDC motor. Ini adalah kaedah yang, beberapa reka bentuk untuk stator, gegelung dan magnet kekal yang dipilih. Selepas itu, ciri-ciri elektromagnet model konvensional yang dipilih dianalisis dan parameter untuk mengurangkan kebocoran fluks dijalankan. Di samping itu, analisis prestasi dicadangkan berlubang-pemutar juga telah dijalankan. Hollow jenis rotor spoke BLDC motor telah direka dan uji kaji dinilai. Keputusan simulasi daripada analisis FEM yang disahkan dengan keputusan ukuran, dalam tempoh emf belakang, tork statik, tork vs kelajuan, kuasa mekanikal, kuasa output, tork dan kecekapan dan menunjukkan bahawa hasil simulasi mempunyai perjanjian yang baik. Ketumpatan tork peningkatan berlubang-rotor hampir dua kali ganda berbanding jenis spoke BLDC motor. Dalam kesimpulan, kajian ini mencadangkan peningkatan baru dalam jenis spoke BLDC motor yang boleh memberikan kepadatan tork lebih tinggi dengan saiz motor yang munasabah. Akhirnya, tesis ini menyediakan garis panduan, cadangan dan mencadangkan struktur yang lebih baik dalam mereka bentuk BLDC motor.*

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A	-	Area
a_g	-	Air gap
b_{sp}	-	Stator pole flux density
BLDC	-	Brushless DC motor
B_r	-	Radial flux density
B_θ	-	Tangential flux density
b_m	-	Magnet flux density
b_{rt}	-	Rotor flux density
c_w	-	Coil width
c_h	-	Coil height
c_s	-	Coil wire diameter
d_1	-	Distance slot opening
FEM	-	Finite Element Method
I	-	Current
m_w	-	Magnet width
m_h	-	Magnet height
m_v	-	Magnet volume
n	-	Speed
N	-	Number of turn
PM	-	Permanent magnet
T_d	-	Torque density

T_c	-	Torque constant
V_{ol}	-	Volume
p	-	Pole
r_1	-	Stator radius
r_2	-	Outer rotor radius
r_3	-	Inner rotor radius
r_1	-	Stator outer diameter
r_2	-	Rotor outer diameter
r_3	-	Inner rotor radius
R_{rp}	-	Reluctance of rotor pole
R_{ag}	-	Reluctance of air gap
R_{sps}	-	Reluctance of stator pole
R_{th}	-	Rotor teeth height
R_{sy}	-	Reluctance of stator yoke
s_{th}	-	Stator tooth height
s_{tw}	-	Stator tooth width
s_{pw}	-	Stator pole width
T	-	Torque
V	-	Voltage
ϕ	-	Flux
η	-	Efficiency

LIST OF PUBLICATIONS

Firdaus, R.N., Norhisam, M., **Farina, S.**, Nirei, M., Wakiwaka, H., Performance Comparison of Conventional Spoke and Hollow-Rotor Permanent Magnet Generator for Small Energy Harvesting Application, 2015. *Journal of the Japan Society of Applied Electromagnetics and Mechanics,* 23 (3), pp. 516-520

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Firdaus, R.N., **Farina, S.**, Suhairi, R., Karim, K. A., Jidin, A., Norhisam, M., Sutikno, T., Design of Hollow-Rotor Brushless DC Motor, 2016. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 7(2). (In press)

CHAPTER 1

INTRODUCTION

This chapter gives a brief explanation about the research project on improvement of torque density spoke type BLDC motor using hollow rotor topology. It consists of project background, problem statement, objectives, thesis contribution, and scope of work. Lastly, the description of the content for each chapter is presented.

1.1 Background

Brushless DC Motor (BLDC) motor has more reliable operation, more efficiency and less noise compared to brushed DC motor. BLDC motor is less heavier as compared with brushed motor with the similar output power. Brushes in a brushed DC motor, wear time being will cause sparking. It is really difficult to control spark problem in a brushed DC motor. Usually, a brushed DC motor could not be used for application which demands long life and reliability. For that reason, a BLDC motor is introduced where it is mostly used in modern devices. BLDC motor is high efficiency, and is suitable for high speed application.

For a BLDC motor, permanent magnet is inserted in the rotor. Coil is been arranged at stator. The operation of a BLDC is based on the simple force interaction between the permanent magnet and the electromagnet. In this condition, when the coil A is energized, the opposite poles of the rotor and stator are attracted to each other. As a result the rotor poles move near to the energized stator. Figure 1.1 shows coil arrangement of a BLDC motor. As the rotor nears coil A, coil B is energized. As the rotor nears coil B, coil

C is energized. After that, coil A is energized with the opposite polarity. This process is repeated, and the rotor continues to rotate. The motor will works but it has one drawback. At any instance only one coil is energized while the other two off coil greatly reduce the power output of the motor because less torque is produce due to only one coil is energized. The DC voltage required for each graph are also shown in Figure 1.1.

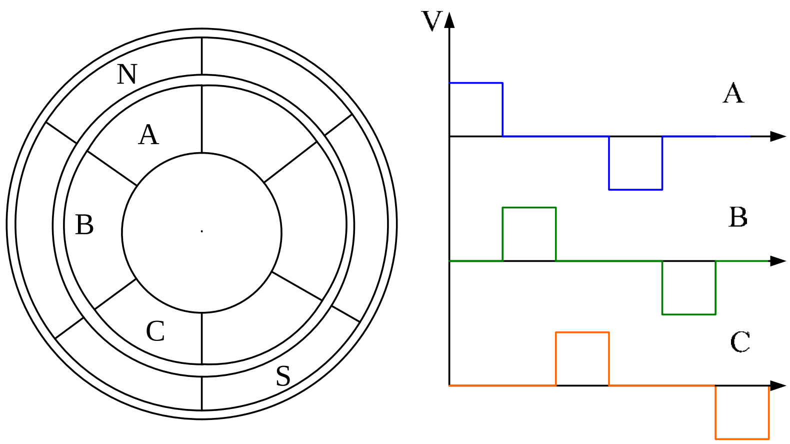

Figure 1.1: Coil arrangement in a BLDC motor (DC voltage)

To overcome this problem, a sensor named as hall effect sensor is used where it can determines rotor position and based on this information, the controller will decides which coils to energize. When coil A is energized, the other coil behind it will be energized too and it will push the rotor to rotates constantly. The combined effects produce more torque and power output from the motor.

This thesis presents improvement of torque density spoke type BLDC motor using hollow rotor topology. The improvement is made from a conventional BLDC motor and a new BLDC motor named as hollow rotor is proposed. Basically, in a conventional type BLDC motor, there will be two magnetic circuit which is in parallel where the first magnetic circuit is at air gap which will be contributing to flux around stator while the other one is below permanent magnet area which will not be used and is called leakage flux as shown in Figure 1.2.

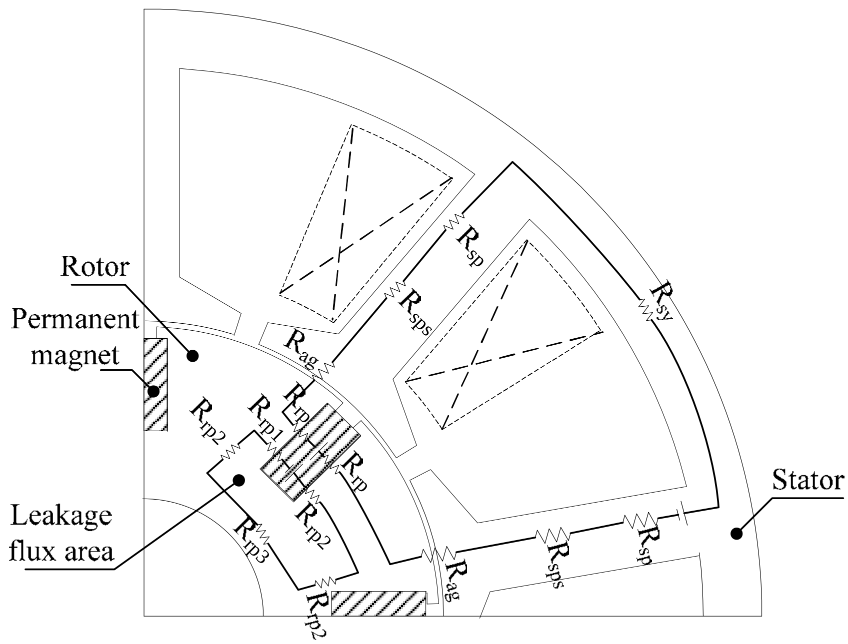

Figure 1.2: Conventional magnetic circuit

To overcome this problem, area below permanent magnet need to be completely filled by hollow. Finite Element Method (FEM) is used to simulate the magnetic characteristic including the torque waveform in this research. The proposed hollow rotor is fabricated and measured. The simulation result by FEM is verified with the measurement result.

1.2 Project Motivation

BLDC motor is commonly used and could be found in many applications such as household application and industrial application such as linear motor, servomotors or actuators for industrial robots. BLDC motor has several advantages compare to other motor type where it has less noise, less maintenance, longer life, spark free, better efficiency and energy saver. Figure 1.3 shows example of spoke type motor construction. The advantage of a spoke type motor are, it has high torque because it uses reluctance torque and magnetic torque simultaneously as stated by Hyung Wook Kim et al. (2013). This had motivated the author to study more on BLDC motor especially spoke type for this research.

Figure 1.3: Spoke type motor construction

1.3 Problem Statement

For high motor performance, BLDC motor needs to be in high torque which will produce high torque density, T_{d}. Therefore, the aim of this research is to produce higher torque density, T_d at similar volume of motor and higher torque constant, T_c with high current application. Many researchers have focused on improving the torque of BLDC motor. For instance, Gyu-Hong Kang et al. (2003) studied irreversible demagnetization of permanent magnet. This irreversible demagnetization characteristics is analysed by rotor structure in term of changing radius of rotor. In a spoke type, the reluctance torque strongly influences the torque characteristics. By considering these characteristics, the motor performance in terms of magnetic flux density will proportionally increase the torque density, as stated by Gyu Hong Kang et al. (2003), Hyung Gyu Kim et al. (2010) and Gyu Hong Kang, Jin hur et al. (2003).

Another example is the study by Byoung-Kuk Lee et al. (2004), who presented a detailed comparative study of spoke type BLDC motor due to operating condition. In this study, flux barriers are designed in order to improve torque characteristics where spoke type motor are developed with some hollow circle between permanent magnet. By using this method, magnetic flux will be concentrated in the air gap. As a result, flux barrier can maximize the torque of the spoke BLDC motor compared to conventional types as stated by Byoung Kuk Lee et al. (2004), Salon (1995) and Gyu Hong Kang et al. (2000). Mizanoor Rahman Mohammad et al. (2013) presented an analytical model for calculating the back emf and the maximum value of air gap flux density in both radial and tangential directions for internal rotor topology. The flux density in the air gap region is derived by considering the stator slot opening as stated by Mizanoor Rahman Mohammad et al. (2013). Another researcher, Hyung Wook Kim et al. (2013) proposed a method for optimizing torque density for developing the neodymium free spoke type BLDC motor. An important step during motor design is the calculation of B_r, the effective air gap flux density. B_r is contributed from the flux of magnet as mentioned by Hyung Wook Kim et al. (2013).

In summary, most of the researchers increase torque density by applying a barrier to reduce the leakage flux. This is because there is a large amount of cycling flux below the permanent magnet of conventional rotor spoke type BLDC motor. In this research, a hollow rotor topology is proposed. By using this method, all flux from magnet will flow directly through stator without having any waste of unused flux compared to other researcher solution.